Magnetospheric MultiScale Mission Navigation Performance Using the Goddard Enhanced Onboard Navigation System

Mitra Farahmand(1)**, Anne Long**(2)**, and Russell Carpenter** (3)
(1)(2) *a.i. solutions, Inc., Lanham, MD 20706, 301.306.1756,*
mitra.farahmand@ai-solutions.com, anne.long@ai-solutions.com
(3) *NASA Goddard Space Flight Center, MS 595.0, Greenbelt, MD 20771, 301.286.7526,*
russell.carpenter@nasa.gov

Abstract: *The Magnetospheric MultiScale (MMS) mission employs an onboard navigation subsystem consisting of the Navigator GPS receiver with Goddard Enhanced Onboard Navigation System (GEONS) software and an Ultra-Stable Oscillator (USO) to satisfy the mission orbit and time determination requirements. The key navigation requirements are derived from the MMS mission-level requirements. The GEONS Ground Support System (GGSS) provides the tools needed to support MMS navigation operations, maneuver planning, and conjunction assessment. During Navigator/GEONS commissioning period, GGSS was used to compare GEONS solutions against independent definitive orbit determination solutions provided by the Flight Dynamics Facility (FDF) at NASA Goddard Space Flight Center (GSFC). The FDF solutions were generated by processing range-rate measurements from Deep Space Network (DSN) contacts and range and Doppler measurements from Space Network (SN) contacts. The results presented in this paper demonstrate that GEONS performance is consistent with the associated MMS definitive and predictive navigation requirements. Furthermore, the GEONS solutions collected prior to the first MMS formation maintenance maneuvers at 160-km confirm GEONS' capability to provide navigation solutions satisfying the maneuver planning requirements throughout the MMS mission.*

Keywords: *Onboard Navigation, MMS, GPS*

1. Introduction

The Magnetospheric MultiScale (MMS) Mission is one of the most complex missions—from a flight dynamics perspective—that NASA Goddard Space Flight Center (GSFC) has ever flown. The science objectives of the MMS mission require a tetrahedral formation of four spacecraft flying in highly eccentric Earth orbits. The regions of prime science interest are the electron diffusion regions of the Earth's dayside magnetopause and the night-side neutral sheet in the magneto-tail. The mission is designed to provide the science data in two phases in which the apogee region of the phase 1 orbit provides long durations in the Earth's dayside magnetopause and the apogee region of the phase 2 orbit provides long durations in the night-side neutral sheet [1].

The MMS mission employs four identical spacecraft spinning at a nominal rate of 3 rotations per minute (rpm) with onboard orbit and time determination provided by the Navigator Global Positioning System (GPS) receiver, the Goddard Enhanced Onboard Navigation System (GEONS) software, and an Ultra-Stable Oscillator (USO). To characterize the expected GEONS performance prior to MMS launch, extensive analyses were performed using realistically simulated GPS measurements [2]. These analyses indicated that GEONS performance is expected to satisfy the MMS navigation requirements.

This paper summarizes the results of the GEONS performance assessment based on flight data collected during the 6-month MMS spacecraft commissioning phase, starting from launch on March 13, 2015. The main objective of this assessment is to confirm that the onboard orbit and time solutions will satisfy the definitive ephemeris and time requirements, predictive ephemeris requirements, and maneuver planning requirements during the science phases of the mission. Section 2 provides an overview of the MMS onboard navigation system. Section 3 discusses the GEONS performance assessment process. Section 4 demonstrates the performance of the Navigator's receiver in providing measurements for GEONS throughout the commissioning phase of MMS mission. Section 5 evaluates the inflight GEONS performance versus the associated onboard navigation requirements. Conclusions are provided in Section 6.

2. MMS Onboard Navigation System

During the MMS mission concept development process, a trade study was performed that determined that the MMS high accuracy orbit and time determination requirements could be satisfied by processing GPS L1 signals acquired by the Navigator receiver in the GEONS Extended Kalman Filter (EKF). This trade study indicated that processing of tracking measurements from ground networks and/or the SN would not provide the high accuracy required to support the MMS mission science objectives for formation sizes as small as 10 km. Navigator's weak signal acquisition capability allows the 12-channel receiver to acquire and track GPS signals well above the GPS constellation. In addition, an onboard navigation system that integrates GEONS with the Navigator receiver was selected to satisfy formation time synchronization requirements as well as to minimize operations cost and complexity.

GEONS estimates the spacecraft's position, velocity, clock bias with respect to GPS time, clock bias rate, and clock bias acceleration using an EKF coupled with a high-fidelity dynamics model to process GPS pseudorange (PR) measurements referenced to the USO. Table 1 lists the GEONS configuration that was selected to fit within the available memory and percentage of the processor usage, while satisfying the MMS navigation requirements. High-resolution thrust acceleration measurements from the onboard accelerometer within the Attitude Control System are included in the EKF to model the frequent formation resize (FR) and formation maintenance (FM) maneuvers. In addition, Navigator performs single point orbit and time solutions (SPS) whenever PR and Doppler measurements from four or more GPS SVs are available.

Table 1. GEONS Configuration on MMS

Model Type	MMS Configuration
Estimator	Factorized EKF
Estimation Frequency	Every 30 seconds for maximum of 12 GPS PR
Nonspherical Earth Gravity Model	13 × 13 JGM-2
Solar/Lunar Ephemeris	Polynomial fit to JPL Definitive Ephemeris (DE)404
Atmospheric Drag	Harris Priester Atmospheric Density

Model Type	MMS Configuration
Solar Radiation Pressure	Spherical Area Model
Integrator	4th order Runge Kutta
Maximum Integrator Stepsize	10 seconds
Maneuver model	Finite Burn using 10-second averaged accelerations

Figure 1 provides an overview of the MMS navigation operations concept. Ground operations support for all MMS spacecraft is provided from a single Mission Operations Center (MOC), which includes a Flight Dynamics Operations Area (FDOA) that supports MMS navigation operations, as well as maneuver planning, conjunction assessment, and attitude ground operations. Reference [1] provides a detailed discussion of the MMS navigation operations concept and the associated ground system operations.

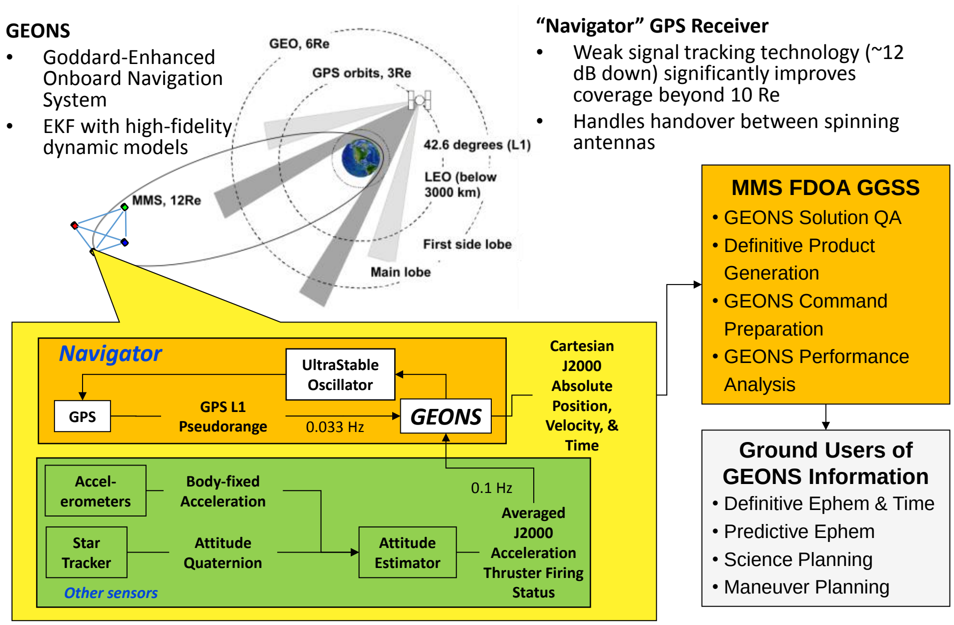

Figure 1. Overview of MMS Navigation Operations Concept

3. GEONS Performance Assessment Process

During the initial nine weeks of the mission when the GSFC Flight Dynamics Facility (FDF) was the primary source of definitive MMS orbit solutions, an extensive analysis was performed to certify the GEONS solutions for MMS navigation. The certification process consist of evaluating GEONS inflight performance with respect to the associated onboard definitive navigation requirements and related ground predictive requirements. GEONS definitive performance is evaluated primarily by comparing GEONS solutions extracted from telemetry data downlinked from the MMS spacecraft versus FDF solutions, assumed as the reference for definitive orbit solutions. Predictive performance is evaluated by comparing the predictive solutions with both the definitive FDF and GEONS solutions. The predictive solutions are generated by propagating

GEONS solutions in the Planning Products segment of the MMS FDOA ground system, which is based on FreeFlyer 6.9.1. The prediction process is configured to use a variable step Runge Kutta 8(9+) integrator with a maximum stepsize of 30 sec, a 21 × 21 EGM96 Earth gravity model, solar and lunar point mass gravity using DE 405, solar radiation pressure, and the Jacchia-Roberts atmospheric density model. The predictive solutions are used to support maneuver planning, conjunction assessment, and Space Network (SN) and Deep Space Network (DSN) contact scheduling and acquisition.

The comparisons are performed using the GEONS Ground Support System (GGSS), which is a component of the FDOA ground system. GGSS is an extensible ground software tool, developed to support space missions that use GEONS as the onboard navigation system. GGSS uses the NetBeans Platform module system as a base, which permits developers to leverage an existing collection of NetBeans plugins. GGSS performs a significant amount of data analysis and product generation using a custom MATLAB toolbox developed for the MMS mission. Because the MMS orbits are highly elliptical, time series trending is not adequate for performance measures that vary significantly over each orbit. Therefore, GGSS also performs period-folded trending in mean anomaly bins for many of the performance measures. Under the assumption that performance measures are approximately stationary within small mean anomaly bins across multiple orbits, period folding permits the computation of statistics such as means and 99% confidence intervals for each bin. Reference [1] provides more detail about the GGSS tool set developed to support MMS navigation operations.

FDF provided orbit determination support for the first nine weeks of the MMS mission. During the remainder of the mission, FDF will maintain a cold backup orbit determination support capability. From the time of spacecraft separation through the first four weeks of the mission, the FDF definitive solutions were computed using the batch-least-squares estimator in the Goddard Trajectory Determination System (GTDS). Starting at April 7, 2015, the FDF definitive solutions were computed using the filter/backward smoother capability in the Orbit Determination Tool Kit (ODTK); these solutions additionally include realistic definitive covariance data [3]. The FDF solutions were generated by processing range-rate measurements from DSN contacts and range and Doppler measurements from SN contacts. Later in the commissioning phase, the Universal Space Network (USN) station at Kiruna, Sweden provided additional Doppler tracking near perigee when SN passes were cancelled or not available. Kiruna Doppler tracking exhibited a relatively large bias throughout the commissioning in both the GTDS and ODTK solutions, which were applied in all GTDS solutions and estimated in ODTK solutions [3]. Throughout the commissioning phase, the MMS satellite spin rate induced a large Doppler noise envelope of varying magnitude depending on the spin rate, which ranged from 3 rpm to 7 rpm [3].

The primary GEONS navigation calibration time span was 2015-133-17:00 UTC through 2015-136-17:00 UTC; this was a “quiescent” period in which no orbit or attitude maneuvers occurred. During this 3-day navigation calibration period, the FDF also delivered ODTK solutions in which the definitive attitude profile was used to model the effects of the MMS spacecraft spin on the tracking measurements. The Doppler residuals were significantly smaller when the spin effects were modeled. These solutions, referred to as “despun” solutions, are used to generate the definitive difference plots for this paper.

4. Navigator Performance

The results included in this section address the Navigator's GPS signal processing performance. The Navigator has proven to be a dependable source of GPS measurements for GEONS even when MMS spacecraft is well above the GPS constellation. Figure 2 displays the number of GPS Space Vehicles (SV) tracked as a function of time and mean anomaly for MMS1. The number of GPS SV decreases near apogee but the average number over consecutive orbits remains greater than five. Simulations performed prior to launch were based on the expectation that four or more GPS measurements would be tracked for only ± 3 hours around perigee. Navigator's performance over the entire MMS orbit during the commissioning period far exceeds these expectations.

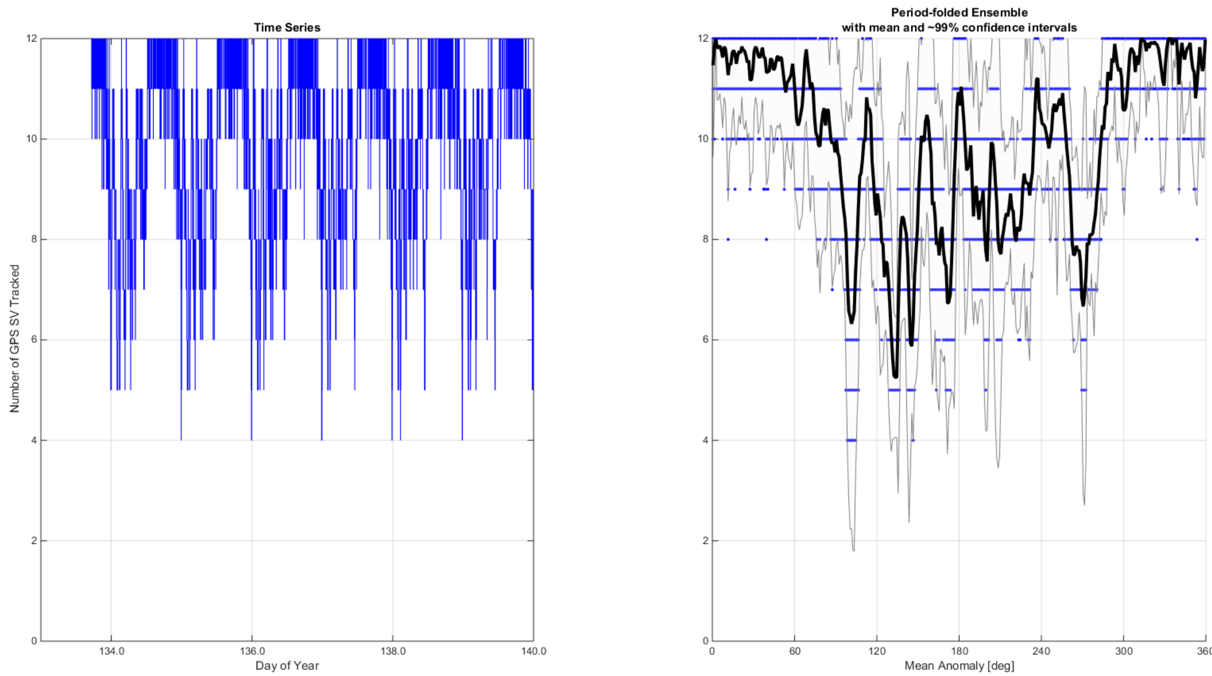

Figure 2. Number of GPS SV Tracked, MMS1

Figure 3 compares the position component and time bias differences between the GEONS and Navigator's SPS solutions. The position component differences in the Velocity (V) / Normal (N) / Binormal (B) frame are within ± 1000 m over the majority of the orbit and within ± 50 m at near perigee. The comparison of GEONS versus FDF solutions (shown in Fig. 5) indicates that the accuracy of the GEONS solutions is significantly higher than the Navigator's SPS solutions.

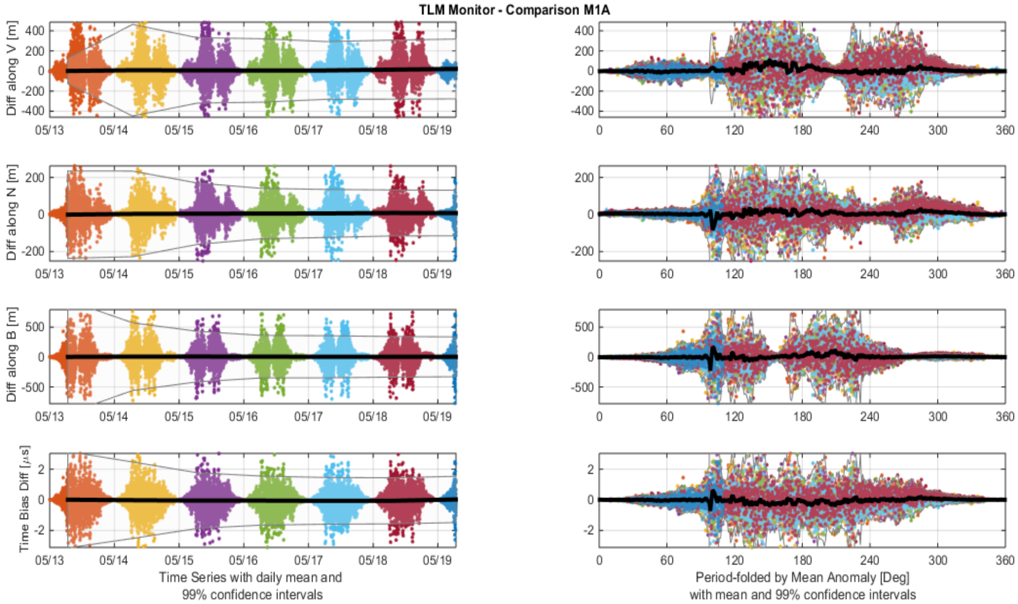

Figure 3. GEONS vs SPS Differences in VNB Position Components and Time Bias for MMS1

5. GEONS Performance Assessment Results

The definitive and predictive navigation requirements are derived from the MMS mission-level requirements. This section evaluates GEONS inflight performance with respect to the associated onboard definitive navigation requirements and related ground predictive requirements. To address GEONS definitive performance, Section 5.1 compares GEONS solutions versus ODTK "despun" solutions delivered by the FDF. To assess predictive requirements, Section 5.2 evaluates FDOA predictive solutions generated from GEONS post-perigee solutions. To assess maneuver planning performance, Section 5.3 discusses results from the time period following the formation initialization maneuvers into 160-km formation size and prior to the formation maintenance maneuvers at 160-km formation size. The results presented in this section demonstrate that GEONS meets all the definitive, predictive, and maneuver planning requirements with significant margins.

5.1. GEONS Definitive Performance

In this section, GEONS performance is evaluated against the following definitive requirements associated with Phase 1a of the mission. For all the requirements stated below, GEONS solutions must satisfy the requirements with 99% probability confidence interval.

Definitive Requirement 1. The absolute orbital positions of the MMS spacecraft shall be known to within 100 km, root-sum-squares (RSS), during the science phases of the mission.

Definitive Requirement 2. The onboard orbit determination system shall provide definitive absolute orbit solutions with a mean semi-major axis (SMA) accuracy of 50 m, for regions above 3 RE except for maneuver recovery.

Definitive Requirement 3. The onboard orbit determination system shall provide definitive relative orbit solutions with a relative mean SMA accuracy of 70 m, for regions above 3 RE except for maneuver recovery.

Definitive Requirement 4. During science operations within the control region of interest (i.e. above 9 RE for Phase 1a), the separation distance between Observatories shall be known to within the greater of 1%, or 100 m.

Definitive Requirements 2 and *3* are examined over the regions above 3 RE except during the maneuver recovery period, which is defined to extend from the maneuver start time to one perigee following the second maneuver. *Definitive Requirements 2* and *3* are based on a Close Approach (CA) limit of 6 km for the Phase 1 formation separations. Carpenter [4] has shown that the in-track errors result primarily from the SMA errors, where the maximum and minimum errors occur at perigee and apogee, respectively. A 10-km CA limit at perigee over 5 orbital revolutions sets a 70-meter limitation on the relative SMA error during Phase 1 (eccentricity = 0.8181, 1.2 RE x 12 RE). The same CA limit yields a 50-meter constraint on the absolute SMA error for each observatory.

Figure 4 compares the FDF and GEONS solutions for MMS1 generated during the prime navigation calibration time span (2015-133-17:00 UTC through 2015-136-17:00 UTC). In the top two subplots in Fig. 4, the RSS position and RSS velocity differences between the GEONS and FDF solutions are plotted in blue. In the third subplot, the SMA difference is plotted in blue. These subplots also show the value of 3 times the formal error of the RSS differences, calculated from the sum of the individual estimator covariance matrices, in red. The percentage of the individual contributions of FDF and GEONS formal variances to the variance of the differences is shown in the green and tan overlays, respectively. The FDF and GEONS RSS differences indicate that the maximum RSS position differences are less than 80 m for all MMS spacecraft. These results confirm that the GEONS navigation solutions meet *Definitive Requirement 1*, delivering absolute orbit determination accuracy with a significant margin below 100 km. In addition, the maximum difference in the FDF and GEONS SMA for all four MMS spacecraft is less than 15 m, well below the 50 m limit; therefore, *Definitive Requirement 2* is satisfied.

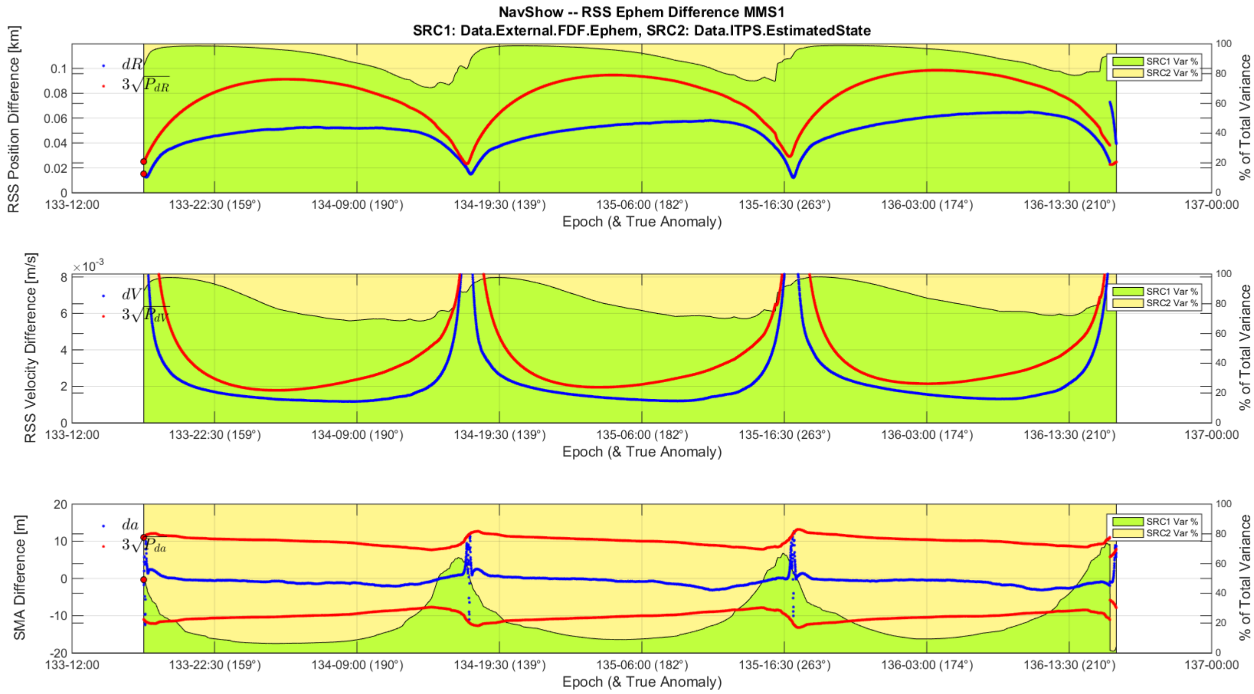

Figure 4. GEONS vs. FDF Differences for MMS1

In Fig. 4, the portion of the formal variance contribution from the FDF solutions (green) for the RSS position and velocity is larger than the portion from the GEONS solutions (tan). This indicates that the FDF navigation solutions are likely to have larger position and velocity error than the GEONS solutions. However, the formal SMA variance calculated for the FDF solutions is smaller than the formal SMA variance for the GEONS solutions. Inspection of the correlation between formal radius and speed errors in the FDF covariance matrices revealed a correlation coefficient unrealistically close to –1, producing unrealistically small SMA variance. This appears to be the result of the poor observability in the FDF solutions since the range data are only available during SN contacts around perigee [3].

The position component and SMA difference plots in Fig. 5 provide additional information for the verification of *Definitive Requirements 1* and *2*. In Fig. 5, the time series subplots on the left and the period-folded subplots on the right extend over the same time span, and the y-limits across a pair of subplots are set to the same value. The grey lines in Fig. 5 indicate the upper and lower 99% probability confidence interval bounds. The plots for all four MMS spacecraft show that the position component differences in the Velocity (V) / Normal (N) / Binormal (B) frame are less than ± 100 m with 99% confidence over the entire orbit. The SMA differences are less than 5 m with 99% confidence, significantly better than *Definitive Requirement 2*.

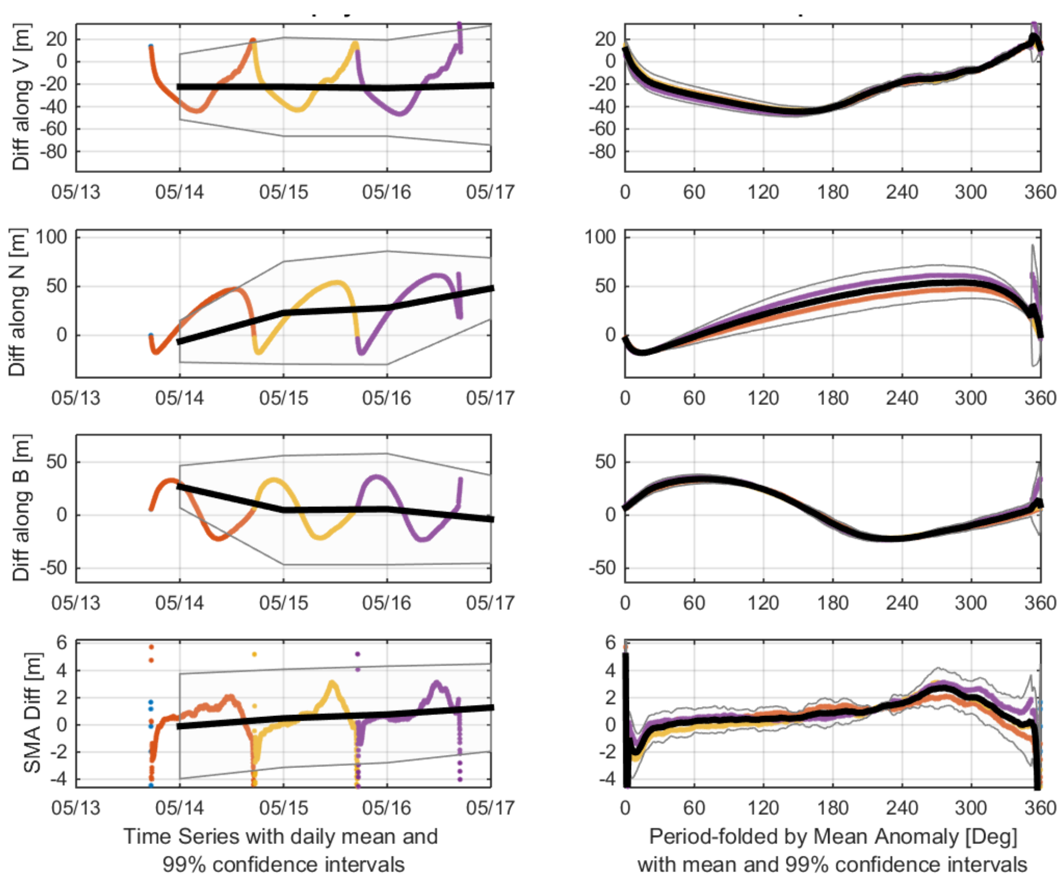

Figure 5. GEONS vs FDF Differences for VNB Position Components and SMA for MMS1

Definitive Requirement 3 is related to *Definitive Requirement 2*. Assuming no correlation in the errors, an estimate of the relative SMA error is given by the RSS of the SMA errors from each MMS. Since the GEONS solutions meet *Definitive Requirement 2* (absolute SMA error is about 5 m), *Definitive Requirement 3* is also satisfied (relative SMA error is about 7.1 m). However, the differences of the Relative SMA (RSMA) values computed based on the FDF solutions for each spacecraft (shown in Fig. 6) and the GEONS solutions (shown in Fig. 7) indicate that the RSMA differences are in fact significantly less than 1 m, due to cancellation of correlated errors.

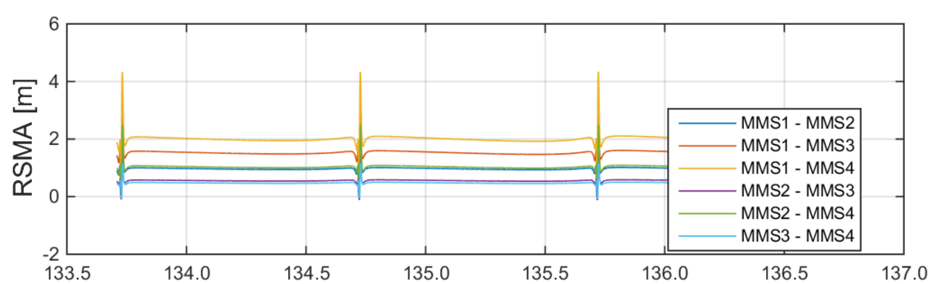

Figure 6. RSMA vs Day of Year based on the FDF Solutions

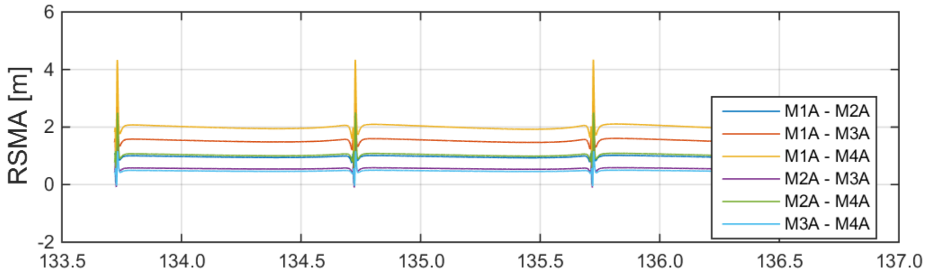

Figure 7. RSMA vs Day of Year based on the GEONS Solutions

Definitive Requirement 4 addresses the accuracy of the separation distance between the MMS spacecraft when in formation over the control region of interest. This is the most demanding requirement set by the MMS mission science objectives. Although the MMS spacecraft were in a string-of-pearls formation and not a tetrahedral formation during the GEONS calibration period, the FDF solutions can still be used to provide definitive reference solutions for assessment of the accuracy of the separation distance. Figure 8 shows the separation distance, also referred to as the Inter-Spacecraft Range (ISR), for each pair of MMS spacecraft during the GEONS calibration period. Figure 9 shows the difference in the ISR for MMS1 and MMS2 computed based on the FDF versus GEONS solutions. For all pairs of MMS, the maximum ISR differences occur at perigee and the ISR over the control region of interest (i.e., above 9 RE in Phase 1, which is apogee ± 7 hours) remains within ± 20 m. In Fig. 9 the control region of science interest is marked by a grey box over consecutive orbits. This result confirms that GEONS solutions can provide 100 m accuracy for the separation distance when MMS spacecraft are in formation in Phase 1, thus satisfying *Definitive Requirement 4*.

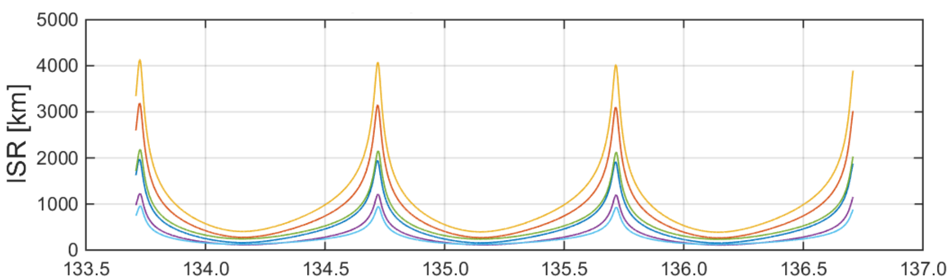

Figure 8. ISR vs Day of Year based on the FDF solutions

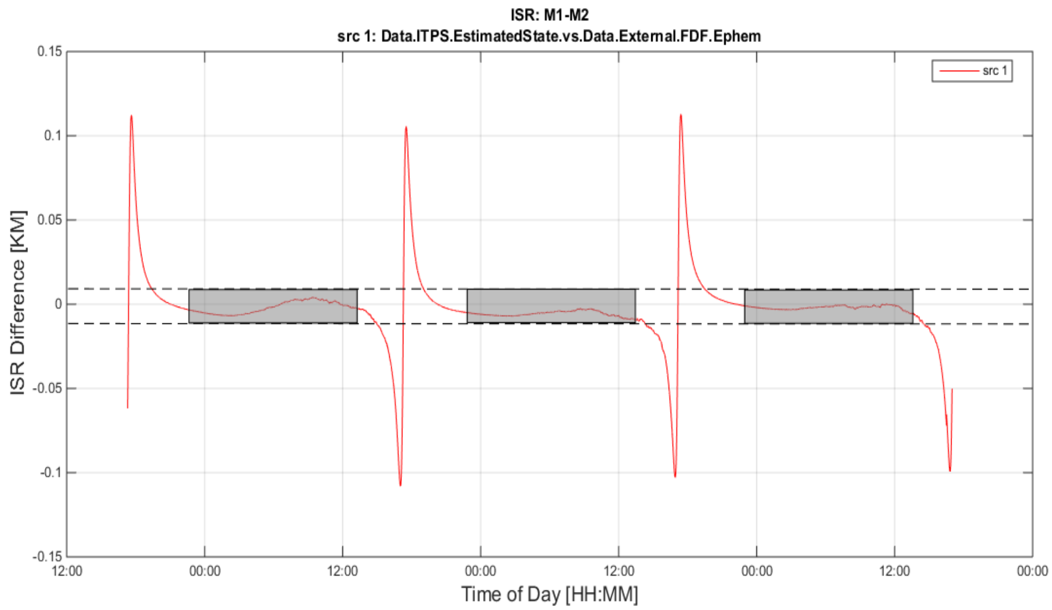

Figure 9. GEONS vs FDF ISR Differences for MMS 1 and MMS 2

5.2. GEONS Predictive Performance

The predictive requirements for MMS spacecraft are based on the accuracy needed for signal acquisition by the Ground-based Networks (DSN, USN) and SN. Throughout the MMS mission, the GEONS post-perigee solutions (or FDF solutions, when available) are used in the FDOA ground system to generate predicted ephemeris data to support telemetry, tracking, and commanding by DSN, USN, and SN. The following requirements are evaluated by comparing GEONS definitive solutions vs FDOA predictive solutions.

Predictive Requirement 1. Provide daily 24-hr predictions of the absolute positions of the MMS spacecraft with a plane-of-sky accuracy of 0.125 deg, with 99 % probability, for acquisition by Ground-based Networks. (Corresponds to RSS position errors not to exceed 27 km in Phase 1a)

Predictive Requirement 2. Provide daily 24-hr predictions of the absolute positions of the MMS spacecraft within 9 second ephemeris error for Nominal Field of View and 7.8 seconds of ephemeris error for Extended Field of View for acquisition by the SN. (Corresponds to RSS position errors not to exceed 19.6 km in Phase 1a)

Figure 10 compares daily 24-hr FDOA ephemeris predictions vs definitive GEONS solutions for MMS1 over six consecutive orbits following formation initialization into a 160-km formation size. The results in Fig. 10 are typical of the differences in prediction observed throughout the commissioning phase, thus providing the means for evaluating the predictive requirements. Since the predicted solutions are initialized with GEONS post-perigee states, the RSS of the difference in GEONS and predicted solutions is negligible at the start of the daily comparison. This difference remains below 80 m after a 24-hr prediction, with maximum differences as the spacecraft approach perigee. These results confirm that the FDOA 24-hr predictions easily meet the *Predictive Requirements 1 and 2*.

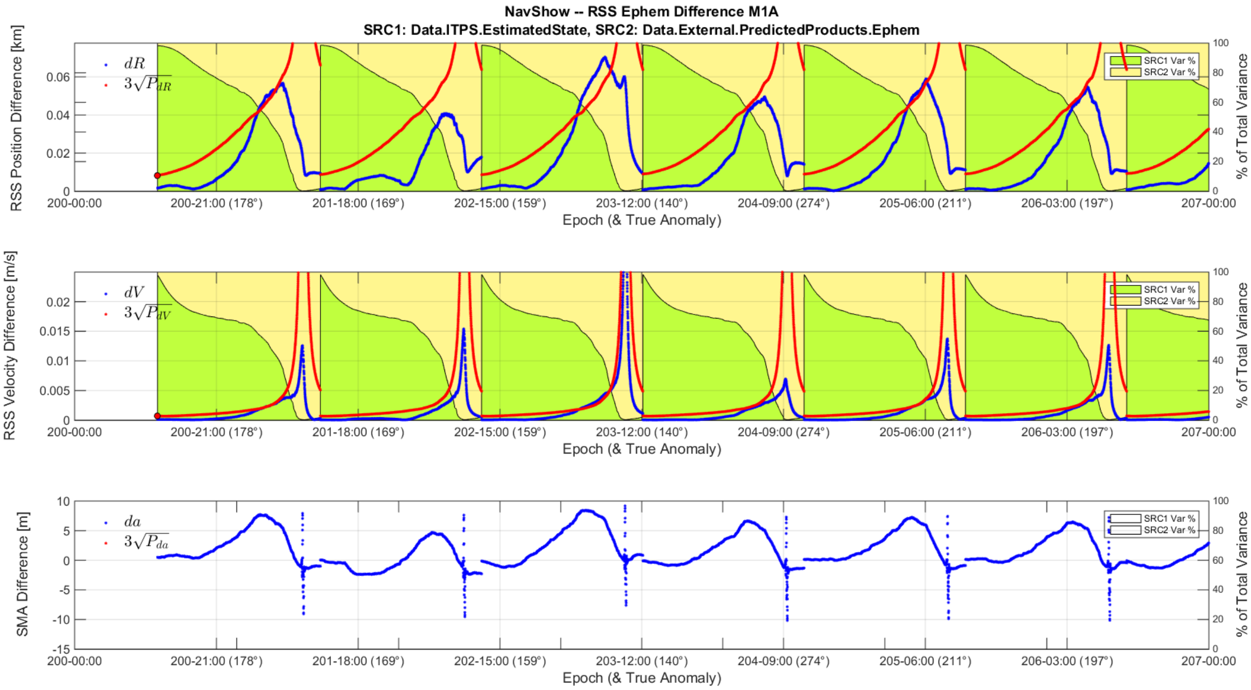

Figure 10. GEONS vs. FDOA Predictions for MMS1

5.3. GEONS Maneuver Planning Performance

In Phase 1a of the MMS mission, the formation is resized from a 160 km down to a 10 km formation size through a series of FR maneuvers. The FR maneuvers are executed as a pair with the first maneuver occurring several hours prior to perigee and the second maneuver occurring within a few hours of the following apogee. Similarly, a pair of FM maneuvers is performed when the quality of the formation has degraded over time. In phase 1a, the following two GEONS-related Maneuver Planning requirements address the FR and FM maneuvers in the order performed.

Maneuver Planning Req 1. For the first maneuver, the error in each component of the predicted velocity vector at the maneuver time shall not exceed the greater of 1% of the associated component of the equivalent impulsive delta-V vector or 10 mm/s, with 99% probability, where the prediction starts at one or two SN post perigee contacts prior to the maneuver.

Maneuver Planning Req 2. For the second maneuver, the error in each component of the predicted velocity vector at the maneuver time shall not exceed the greater of 1% of the associated component of the equivalent impulsive delta-V vector or 2 mm/s, with 99% probability, where the prediction starts at the SN post-perigee contact following first maneuver.

The FR and FM maneuvers are executed when the DSN is in contact with the maneuvering spacecraft. Therefore, the DSN contact schedule dictates the time of the maneuvers. In operation, maneuver planning requirements are evaluated over consecutive orbits prior to the maneuver time for which the prediction ephemeris starts with the GEONS solutions downlinked during SN post perigee contacts. To verify *Maneuver Planning Req 1*, the velocity errors are examined from the start of the maneuver planning prediction (30 deg in mean anomaly) to the latest time that the first maneuver can be scheduled, which corresponds to 3 hours prior to the following perigee (315 deg in mean anomaly). To evaluate compliance with *Maneuver Planning Req 2*, the velocity component differences are examined from 30 deg in mean anomaly to the latest possible time for the second maneuver, which corresponds to 5 hours post apogee (255 deg in mean anomaly).

Three weeks following initialization to a 160 km formation size, a set of FM maneuvers was performed on orbits 139 – 140 (July 30). In this section, the data collected over six consecutive orbits prior to the first FM maneuver on orbit 139, FM 139, are presented. Table 2 displays the values of planned delta-V for FM 139 for the maneuvering spacecraft (MMS1 and MMS 4) and the threshold for the error set by *Maneuver Planning Req 1*. Figures 11 and 12 show the velocity component differences in the J2000 inertial frame for one-orbit and two-orbit predictions (as implied in *Maneuver Planning Req 1*) for MMS 1. The grey dashed box on each subplot in Fig. 11 and 12 displays the region for which *Maneuver Planning Req 1* is applied to MMS 1. Note that the requirement applies only up to the start of FM 139, which happens to be at 315 deg in mean anomaly (the latest time to schedule the first maneuver). Also, the grey box vertically extends to the requirement threshold values on each velocity component applied to MMS 1, which in this case are above the minimum value of 10 mm/s. The results confirm that the maneuver planning predictions based on GEONS solutions satisfy *Maneuver Planning Req 1* for these maneuvers with a large margin.

Table 2. FM 139 delta-V Values and the Associated Requirement

MMS	**FM 139 delta-V (mm/s) [vx, vy, vz]**	**1% of delta-V (mm/s) [vx, vy, vz]**	**Req. 1 threshold (mm/s) [vx, vy, vz]**
MMS 1	[-1314.5,1566.9,-2260.5]	[-13.145,15.669,-22.605]	[13,15,22]
MMS 4	[931.1,-3.3,-119.1]	[9.311,-.033,-1.191]	[10,10,10]

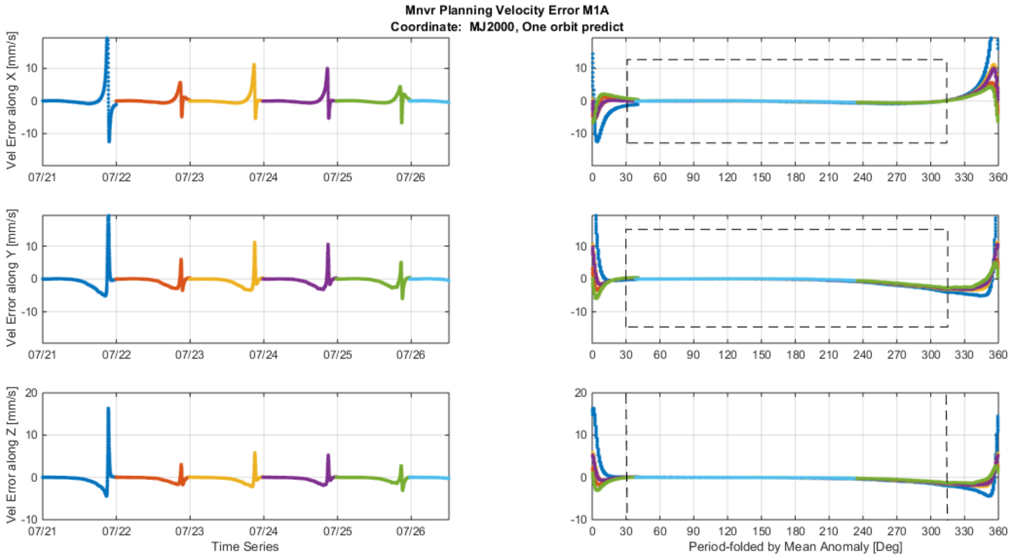

Figure 11. Velocity Differences for One-orbit Predictions Prior to FM 139

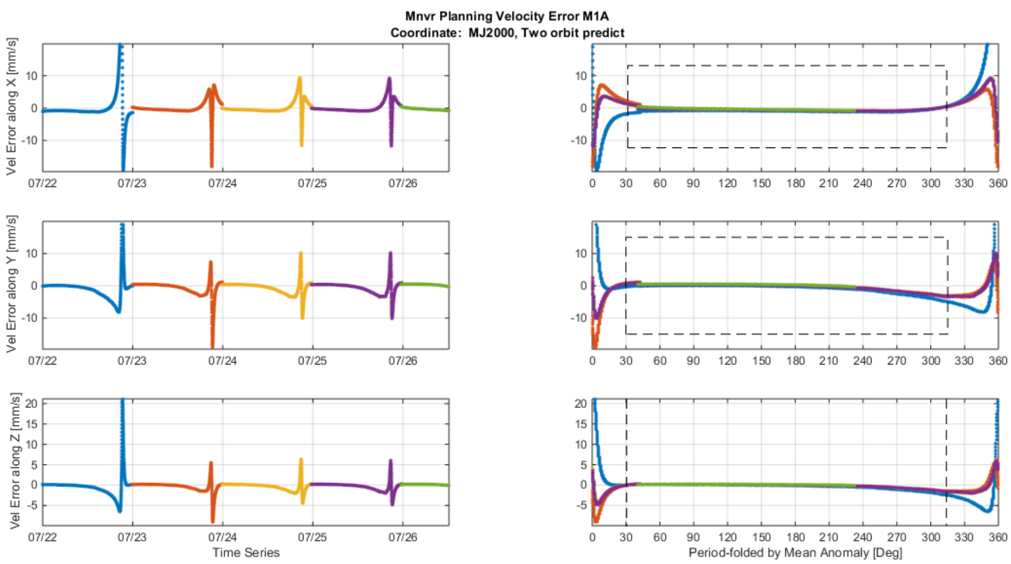

Figure 12. Velocity Differences for Two-orbit Predictions Prior to FM 139

To evaluate *Maneuver Planning Req 2*, the velocity component differences post FM 139 are examined from 30 deg in mean anomaly to the start of the second FM maneuver, FM 140, which for both MMS 1 and MMS 4 occur prior to 255 deg in mean anomaly (i.e. the latest possible time for the second FM maneuver). Table 3 displays the values of planned delta-V for FM 140 for MMS1 and MMS 4 and the threshold for the error set by *Maneuver Planning Req 2*. Figures 13 and 14 show the velocity component differences in the J2000 inertial frame for a one-orbit prediction. In Fig. 13 and 14, the data corresponding to the orbit following FM 139 and prior to

FM 140 is plotted in yellow. The grey dashed box on each subplot in Fig. 13 and 14 displays the region for which *Maneuver Planning Req 2* is applied to MMS 1 and MMS 4, respectively. Note that from Table 3, the requirement threshold applied to MMS 1 and MMS 4 extend above the minimum value of 2 mm/s. The results demonstrate that the maneuver planning predictions based on GEONS solutions satisfy *Maneuver Planning Req 2* for these maneuvers.

Table 3. FM 140 delta-V Values and the Associated Requirement

MMS	**FM 140 delta-V (mm/s) [vx, vy, vz]**	**1% of delta-V (mm/s) [vx, vy, vz]**	**Req. 2 threshold (mm/s) [vx, vy, vz]**
MMS 1	[1183.2,-352.7,1393.5]	[11.832,-3.527,13.935]	[12,4,14]
MMS 4	[-339.3,301.7,839.9]	[-3.393,3.017,8.399]	[3,3,8]

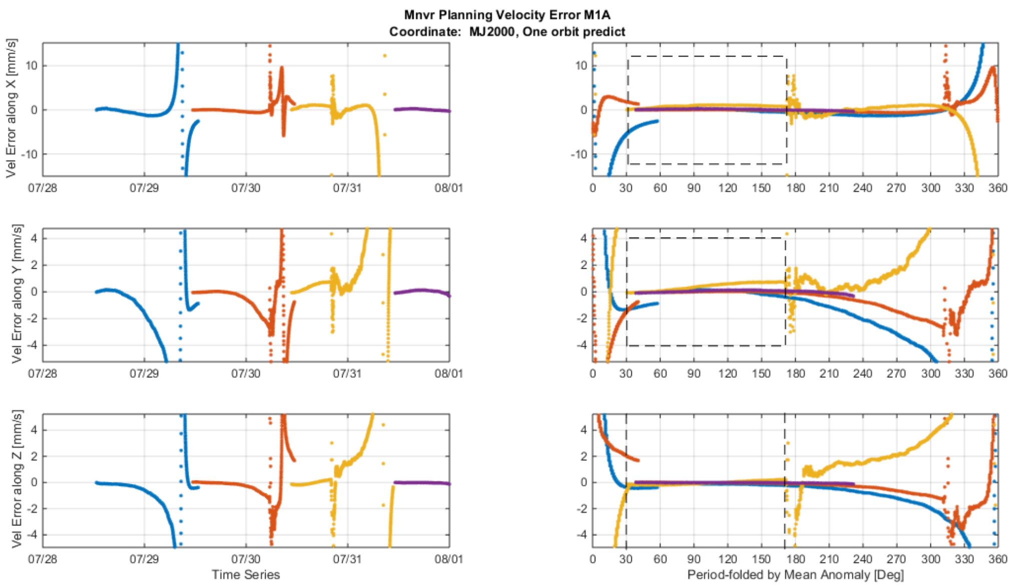

Figure 13. Velocity Differences for One-orbit Predictions Prior to FM 140, MMS 1

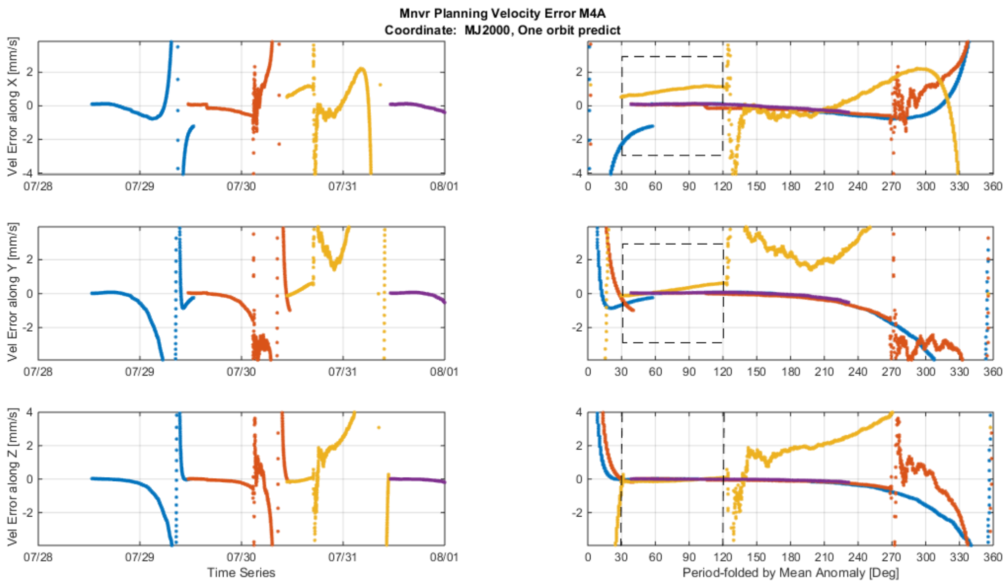

Figure 14. Velocity Differences for One-orbit Predictions Prior to FM 140, MMS 4

6. Conclusions

Navigator/GEONS performance during the MMS commissioning phase has exceeded expectations. Starting immediately following GEONS initialization, GEONS navigation solutions showed a close comparison to the FDF definitive solutions. Prior to completion of the GEONS navigation calibration, the GEONS solutions were used extensively to generate definitive, predictive, and maneuver planning products. Starting with the perigee-raise campaign on orbit 7, all MMS maneuvers were successfully planned using GEONS solution states because of indications that the GEONS solutions were more accurate than the FDF solutions based on DSN/USN and SN tracking.

Section 4 confirms that the Navigator receiver provides high accuracy GPS measurements to GEONS for generating consistently accurate orbit determination solutions over the entire MMS Phase 1 orbit. The results shown in Section 5 demonstrate GEONS excellent performance in meeting or exceeding all the definitive, predictive, and maneuver planning requirements to support the MMS mission operations and science objectives.

The Navigator / GEONS performance during the commissioning phase has been a success and it is expected to continue as the Phase 1a of the mission commences. GEONS navigation analyses continue throughout the mission to provide a better assessment of the navigation solutions over different periods of the mission.

7. Acknowledgement

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8. References

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